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In this report, we give a brief summary of the work done by the PI and his students on the design and analysis of robust feedback systems. Under this contract, we have conducted research on a number of problems in robust control and identification theory. In particular, we have obtained significant new results on H_2 , H_∞ , and H_2/H_∞ control theory, robust digital control in the framework of sampled-data systems, identification in H_∞ , etc. In this report, we will present a brief summary of the main results obtained under the AFOSR contract.

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Final Report for the AFOSR Contract AFOSR- 90-0053 The Design and Analysis of Robust Feedback Systems

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Abstract

In this report, we give a brief summary of the work done by the PI and his students on the design and analysis of robust feedback systems. Under this contract, we have conducted research on a number of problems in robust control and identification theory. In particular, we have obtained significant new results on \mathcal{H}_2 , \mathcal{H}_∞ , and $\mathcal{H}_2/\mathcal{H}_\infty$ control theory, robust digital control in the framework of sampled-data systems, identification in \mathcal{H}_∞ , etc. In this report, we will present a brief summary of the main results obtained under the AFOSR contract.

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1 Introduction

Our research under the AFOSR contract no. AFOSR- 90-0053 has focused on various problems in robust control. We have conducted research on the following topics:

- \mathcal{H}_2 , \mathcal{H}_∞ , and Robust Control Theory
- Multiple Objective Controller Synthesis — \mathcal{H}_2 , \mathcal{H}_∞ , and Mixed $\mathcal{H}_2/\mathcal{H}_\infty$ Problems
- Robust Control Analysis and Synthesis for Sampled-Data Systems
- Modeling for Robust Control — Model Validation, Frequency Domain Identification in \mathcal{H}_∞
- Implementation of Gain Scheduled Controllers for Nonlinear Robust Control
- Engineering Applications of Robust Control

Our work in all these areas has been fully and extensively documented in a number of journal and conference publications which are widely accessible. A complete list of these publications is a part of this final report. To give a detailed exposition of all the results in these papers will lead to a rather lengthy final report. As such, we will only give general descriptions of the results. Precise mathematical formulations, statements and proofs of the results can be found in the relevant publications as references below.

2 \mathcal{H}_2 , \mathcal{H}_∞ and Robust Control Theory

In the initial period of this contract, we continued our research into state-space time-domain approach to the various problems in \mathcal{H}_∞ control theory. A very simple state-space time-domain proof of the fundamental result of \mathcal{H}_∞ control theory was given in [1]. This proof is remarkable in that it only uses the most well known results on the LQR problem as contained in the classic paper by Willems. Thus, our proof made strong technical connections with certain optimization problems treated by Willems.

In a related direction, the problem of designing a controller to render a given closed loop transfer function positive real is treated in [28, 56]. We also treated \mathcal{H}_∞ control problems for sampled-data systems. This will be discussed later in this report.

Generalization of the state-space approach to the time-varying case was carried out in [3], [5], and [30]. The finite horizon case was solved in [3] and the infinite

horizon case in [5, 30]. Note that stability becomes an important issue in the infinite horizon case while it is irrelevant in the finite horizon case.

Most of the literature in \mathcal{H}_∞ control theory assumes that the initial conditions are zero. The case of nonzero initial conditions was treated in [4] and [29]. In this case, even for linear time-invariant systems, the controller turns out to be linear time-varying. The controller is given by Riccati differential equations rather algebraic Riccati equations. These results are the precise generalizations of the classical (transient) LQG control results to the \mathcal{H}_∞ setting.

A fairly general state space approach to robust performance problems has been obtained in [43]. In this paper, we have shown how many robust performance problems can be reduced to finite-dimensional convex optimization problems. These results, however, are restricted to state-feedback and use quadratic stability type definition of performance. We also showed that our approach is less conservative than the scaled small gain theorem (with constant scalings) approach which is related to μ synthesis.

We have also investigated normalized coprime factorizations. State space formulae for such factorizations for linear time-varying systems were given in [13] and [31]. The related graph topology was investigated in [14]. We showed [25] that in the state-feedback case, *a maximally robust controller for stabilization of plants with normalized coprime factor uncertainty is given by an LQR gain.*

The problem of optimal \mathcal{H}_2 control subject to a pole placement constraint is treated in [26]. The results in this case are very general. Among other things, we show that the order of the optimal controller need not exceed that of the generalized plant.

The structured singular value analysis was extended to unstable uncertainties in [34]. The case of time-varying perturbations for robust stability analysis with structured uncertainty is treated in [44].

3 Multiple Objective Controller Synthesis

Design of control systems almost invariably involves tradeoffs among competing objectives. It is often the case that there are several different performance and robustness goals, and all of these can not be met simultaneously. For example, it is intuitively clear that to obtain a greater robust stability margin, it is likely that one will need to settle for a reduction in the performance of the control system. From this point of view, one should postulate the controller synthesis problem as the problem of studying tradeoffs among competing objectives.

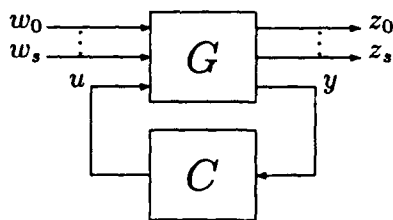


Figure 1: The synthesis framework

Consider the feedback system shown in Fig. 1. The plant to be controlled is denoted by G , while the controller is denoted by C . The exogenous inputs are w_0, \dots, w_s (these are signals such as sensor noises, load disturbances, commands, input channels for modeling uncertainty). The controlled or regulated outputs are z_0, \dots, z_s (these signals represent weighted tracking errors, weighted actuator inputs, output channels for modeling uncertainty). The control input vector is u while the measured output vector is y . The input-output operator from w_h to z_h will be denoted by $T_h(C)$. We are primarily interested in performance measures of the form

$$J_h(C) := \|T_h(C)\|_{\alpha_h},$$

where α_h indicates the norm of interest. Typically, $\alpha_h = 2, \infty, \mathcal{A}$. These norms are the most commonly used system norms in robust control. We have obtained the following results:

- In the state-feedback case, we have given sufficient conditions (which are also necessary under some mild rank conditions) [2] and [45] for the following mixed $\mathcal{H}_2/\mathcal{H}_\infty$ problem:

$$\nu(G) := \inf\{\|T_0(C)\|_2 : \|T_1(C)\| < 1\}. \quad (1)$$

These conditions are given in terms of algebraic Riccati equations. In addition, we have also given a formula for the controller.

One interesting feature of the results is that *even though the states are available for feedback, the controller need not be static*. As a matter of fact, we gave an example where there is no static state-feedback solution to this problem, but there is a dynamic state-feedback controller that solves the problem.

These results have been further generalized to *several* performance objectives in [54].

- We have given a complete solution [6, 47] to the mixed $\mathcal{H}_2/\mathcal{H}_\infty$ problem formulated by Bernstein and Haddad. In contrast to the existing solutions which are in terms of couple matrix Riccati equations for which no established solution procedures exist, our solution is given in terms of one algebraic Riccati equation and a finite dimensional convex optimization problem.

The main results show that if all the states are available for feedback, then there is a static state-feedback solution if the \mathcal{H}_∞ constraint is feasible. In the output feedback case, the controller order need not exceed the plant order.

We also showed that in some examples the optimal $\mathcal{H}_2/\mathcal{H}_\infty$ solution lies at the boundary of the \mathcal{H}_∞ constraint. In other words, for the optimal solution, the \mathcal{H}_∞ norm of $\|T_1\|_\infty$ is exactly equal to the given upper bound for it. This impacts some of the results along the Riccati equation approach to this problem.

These results have been generalized to the discrete-time case in [17] and [40]. The discrete-time case differs technically from the continuous-time case in several significant ways.

Also, an extension of these ideas to the case of "generalized \mathcal{H}_2 norm has been carried out in [38]. The above results have also been generalized to $\mathcal{H}_2/\mathcal{H}_\infty$ filtering in [53].

- A very different multiple objective control problem is to design a controller that is robustly stabilizing while also providing asymptotic disturbance rejection against step and sinusoidal type inputs. This is a robust regulation problem. We gave a solution to this problem for step type exogenous inputs in [49].

An overview of some of these results was given in the book chapters [50, 55].

4 Robust Control Analysis and Synthesis for Sampled-Data Systems

With the rapid advances in digital technology and computers, a large number of controllers are being implemented on digital computers. The physical process, the regulated and the exogenous signals evolve in continuous-time while the controller samples the measured output and processes the resulting data digitally to generate a sequence of discrete control inputs. The plant and the digital controller are interfaced using *analog-to-digital* (A/D) and *digital-to-analog* (D/A) converters. Such an interconnection of a continuous-time system and a discrete-time system is called a *Sampled-Data System*. The conventional methods for design of digital control systems rely on a number of approximations which are valid for sufficiently fast sampling rates, but are usually suboptimal and conservative.

In the last few years, a number of researchers have been focusing their efforts on developing new techniques for the analysis and synthesis of robust sampled-data systems. This research direction has the promise of providing tools for the analysis and design of digital control systems and understanding tradeoffs between sampling rate,

performance, and robustness. We have obtained several results aimed towards developing a rigorous theoretical basis for the analysis and synthesis of robust sampled-data feedback control systems. These results are summarized below.

- A formula for the \mathcal{L}_∞ -induced norm for sampled-data systems and an approximation procedure to evaluate it has been derived [18] and [33]. This formula brings out the inter sample behavior of the sampled-data system in a very natural manner.

The problem of computation of the \mathcal{L}_2 induced norm (or \mathcal{H}_∞ norm) of sampled-data systems was treated in [20] and [41]. The computational burden involves solving discrete algebraic Riccati equations, and a Riccati differential equation over one sampling period.

- We have obtained a direct solution to the \mathcal{H}_∞ controller synthesis problem [19], [35], and [42] without converting the problem to an equivalent discrete-time problem. We have shown that this problem can be solved in terms of existence of solutions to two Riccati equations and invertibility of a certain matrix function over one sampling period. Our work also leads to an *optimal hold function* for this problem. Indeed, in the standard notation of \mathcal{H}_∞ theory, the optimal hold function turns out to be $e^{(A+\gamma^{-2}B_1B_1'X_\infty-B_2B_2'X_\infty)t}$, $t \in [0, T]$. In some very recent work, we have obtained some results on the computation of the \mathcal{H}_∞ norm for sampled-data systems.
- We have given a new definition of the \mathcal{H}_2 norm for sampled-data systems and a synthesis procedure for \mathcal{H}_2 optimal control [10] and [36]. The previous definition of the \mathcal{H}_2 norm given by Chen and Francis was as follows: Apply a Dirac delta function input to the closed loop system at time zero. Then the square root of the integral square of the output time function is defined to be \mathcal{H}_2 norm of the closed loop system. This definition is obviously motivated by the analogous definition of the \mathcal{H}_2 norm for standard linear time-invariant continuous-time systems. However, a key difference is not taken into account: a sampled-data system is periodic, not time-invariant. In other words, there is no a priori reason to assume that the delta function input is applied at time zero. We defined the \mathcal{H}_2 norm as the square root of the average integral square of the output time function with the input being the delta function anywhere in a sampling interval. This definition is consistent with the stochastic interpretation of the \mathcal{H}_2 norm: \mathcal{H}_2 norm is square root of the average steady state variance of the output assuming the input to be zero mean white Gaussian stochastic process of unit covariance.
- We have obtained necessary and sufficient conditions for robust stability for both \mathcal{L}_2 and \mathcal{L}_∞ signal settings [16, 51]. We have considered both structured and unstructured uncertainty cases. We have also shown that robust performance is equivalent to a "larger" robust stability problem. These results are generalizations of standard results on robust stability and performance for LTI systems

to the setting of sampled-data systems. The main deficiency of these results is that the necessity of the robust stability conditions is established under the assumption that the uncertainty can be either an arbitrary norm bounded linear time-varying or periodic operator. This may lead to unnecessary conservatism in the robust stability tests.

These results constitute substantial contributions to the subject to robust sampled-data control system analysis and design. We have covered almost all aspects of this problem area.

In a somewhat related direction, we gave solutions to discrete-time decentralized control problems using periodic feedback in [21] and [12].

5 Robust Identification or Identification for Robust Control

The problem of robust identification or identification for robust control is an emerging area of research. While there is no consensus yet on the technical problem formulation, it is widely believe that this is an important area. Simply put, we have to make system modeling compatible with control design. A number of research directions are being currently pursued in this area.

Our work under this contract has focused on the problem of identification in \mathcal{H}_∞ . The basic problem is: suppose we are given noisy frequency data for stable linear time-invariant system. Find an identified model such that the worst case identification error is optimal and had good asymptotic properties. We have obtained a number of results on some very effective and easily computable solutions to the problem of identification in \mathcal{H}_∞ [8, 48, 9, 37, 11, 15, 52, 23]. Our algorithms are very easy to implement. They apply to continuous-time as well as discrete-time systems. The algorithms are computationally efficient and allow design tradeoffs between noise and modeling errors. They involve standard numerical tools such as FFT, singular value analysis, etc. We have written a MATLAB based package to implement our algorithms. We applied [57] these algorithms to some real data that was obtained from Dr. D. Bayard of JPL on a flexible structure. Unfortunately, our algorithms were not as successful as we had hoped. The main reason was that the structure is very lightly damped with a large number of modes. This paper [57] showed that much more work is needed on the problem of identification for control.

The related problem of finite-dimensional approximation of unstable infinite-dimensional systems was treated using frequency domain methods in [7, 32].

We have also shown the robust convergence of the least squares parameter estimation algorithm in the presence of worst case bounded noise [22].

6 Gain Scheduled Controllers for Nonlinear Control

Gain scheduling is perhaps the most commonly used practical method for designing robust controllers for nonlinear systems. In the last phase of our work under this contract, we investigated the issue of implementation of gain scheduled controllers. Recently, we have obtained a method [27] for implementation of gain scheduled controllers for nonlinear systems that has the useful property that the robustness and stability properties of the linear design are locally preserved for the closed loop nonlinear system. We expect that this area of investigation will grow further during the next few years as we approach robust nonlinear control.

7 Engineering Applications

One of our main aims in this research has been application of modern robust control to problems of importance to air force and engineering in general. In collaboration with I. Kaminer who was a Boeing engineer and later became a Ph. D. student of the PI, we have applied some of the robust control theory to design of controllers for airplanes [46]. We also have a collaboration with Dr. A. Pascoal, Portugal, on applying robust control methods to an autonomous underwater vehicle [39]. In this application, our control laws will be implemented on the physical vehicle which is being constructed now. The work on implementation of gain scheduled controller discussed above will also find its application here. Finally, in a major interdisciplinary effort, I am involved in application of control technology to semiconductor manufacturing equipment. This is a wide ranging applications effort to an important area of national and international economy.

List of publications of P. P. Khargonekar and his group supported by Air Force
Office of Scientific Research Contract no. AFOSR- 90-0053

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